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Technical Support Package

Optimal Tuner Selection for Kalman-Filter-Based Aircraft Engine Performance Estimation

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for

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Optimal Tuner Selection for Kalman-Filter-Based Aircraft Engine Performance Estimation

Brief Abstract

This technology is a linear design methodology for minimizing the error in on-line Kalman filter-based aircraft engine performance estimation applications. This technique specifically addresses the underdetermined estimation problem, where there are more unknown parameters than available sensor measurements. A systematic approach is applied to produce a model tuning parameter vector of appropriate dimension to enable estimation by a Kalman filter, while minimizing the estimation error in the parameters of interest. Tuning parameter selection is performed using a multi-variable iterative search routine that seeks to minimize the theoretical mean-squared estimation error of the Kalman filter. Experimental simulation results based on this technique have been found to be in agreement with theoretical predictions. The new methodology is able to yield a significant improvement in on-line engine performance estimation accuracy.

Section I — Description of the Problem

General description of problem/objective: An emerging approach in the field of aircraft engine controls and health management is the inclusion of real-time onboard models for the in-flight estimation of engine performance variations. This technology, typically based on Kalman filter concepts, enables the estimation of unmeasured engine performance parameters that can be directly utilized by controls, prognostics, and health management applications. These real-time onboard models typically reside within an onboard engine control computer. A challenge that complicates this practice is the fact that an aircraft engine's performance is affected by its level of degradation, generally described in terms of unmeasurable health parameters such as efficiencies and flow capacities related to each major engine module. Through Kalman filter-based estimation techniques, the level of engine performance degradation can be estimated, given that there are at least as many sensors as parameters to be estimated. However, in an aircraft engine the number of sensors available is typically less than the number of health parameters, presenting an under-determined estimation problem. A common approach to address this shortcoming is to estimate a subset of the health parameters, referred to as model tuning parameters. The problem/objective is to optimally select the model tuning parameters to minimize Kalman filter-based estimation error.

Key or unique problem characteristics: Engine performance deterioration effects are typically represented within aero-thermal engine models through a vector of component health parameters in a linear state space formulation. Because engine performance deterioration occurs gradually on a very slow time scale, health parameters are typically modeled without dynamics. The model's vector of state variables can be augmented with the vector of health parameters allowing the health parameters to be estimated applying Kalman filter concepts, as long as there are more sensed measurements than unknown health parameters. However, in typical aircraft engine applications an underdetermined estimation scenario exists where there are more unknown health parameters than available sensor measurements. The challenge to aircraft engine performance estimation under dynamic operating scenarios becomes one of minimizing the impact of deterioration-induced parameter estimation errors.

Prior art: The conventional approach to developing onboard real-time adaptive engine models based on Kalman-filter concepts is to select a subset of health parameters to serve as model tuning parameters. This approach will enable the Kalman filter to tune the onboard model so that the model's outputs track measured (sensed) engine outputs. However, other unmeasured engine outputs will not be accurately represented by the onboard model due to the fact that the impact of the entire vector of health parameters will not be accurately represented within the Kalman filter model. Recently Mr. Jonathan Litt (NASA GRC) demonstrated that improved Kalman filter estimation accuracy could be obtained by applying a fundamental change in the approach of selecting a Kalman filter's tuner vector. This prior technique selected tuner vectors which were a linear combination of all health parameters, not simply a subset of health parameters, by applying a singular value decomposition technique. However, this approach is ad hoc, and does not fully capture the overall systematic effects of tuner selection of Kalman filter estimation error. Reference: Litt, J.S., (2008), "An Optimal Orthogonal Decomposition Method for Kalman Filter-Based Turbofan Engine Thrust Estimation," Journal of Engineering for Gas Turbines and Power, Vol. 130 / 011601-1**.**

Disadvantage of prior art: The disadvantage of the two prior Kalman filter tuner selection approaches mentioned above are that they do not systematically minimize the effects of engine performance deterioration on the Kalman filter estimation error**.**

Section II — Technical Description

A general description of the innovation is contained in the following conference paper (not yet published at the time of this reporting), to be presented in June 2009 at the ASME Turbo Expo conference: Simon, D.L., Garg, S., "Optimal Tuner Selection for Kalman Filter-Based Aircraft Engine Performance Estimation," ASME GT2009-59684, Orlando, FL, June 8-12, 2009.

Purpose and description of the innovation: The purpose of the innovation is to provide a systematic approach to select a reduced-order model tuning parameter vector of low enough dimension to be estimated, while minimizing the mean squared estimation error using a Kalman filter estimator. This approach can significantly reduce the error in onboard aircraft engine parameter estimation applications such as model-based diagnostic, controls, and life usage calculations.

Identification of methodology steps: Step 1. Obtain linear state space equations representative of engine dynamic performance, including performance deterioration effects. These models can be readily extracted from non-linear aerothermal engine models as is commonly done for aircraft engine controls and diagnostics applications; Step 2. Define the measurement noise covariance matrix, and the health parameter (deterioration) covariance matrix; Step 3. Based on the linear state space equations obtained in step 1 and the covariance matrices obtained in step 2 construct the Kalman filter mean sum of square estimation errors (SSEE) equation for an arbitrary transformation matrix applied for converting the full-order health parameter vector into a reduced order tuning parameter vector. Detailed derivation of the

Kalman filter SSEE equation can be found in the above noted conference paper; Step 4. Apply an iterative optimal search to produce the transformation matrix, and the reduced order tuning parameter vector, which will minimize the Kalman filter SSEE in the parameters of interest; Step 5. Verify that Kalman filter SSEE meets application accuracy requirements.

Functional operation: Prototype coded and operable in the Matlab environment

Supportive theory: The conference paper noted above fully derives the theoretical basis for methodology. Theoretical predictions of estimation accuracy have been experimentally validated.

Engineering specifications & peripheral equipment: Coded in Matlab and utilizes a Matlab function to conduct required iterative search.

Section III — Unique or Novel Features of the Innovation

Novel or unique features: Novel features include 1. The derivation of the mean Kalman filter sum of squared estimation errors for an arbitrary reduced order tuner vector defined as a linear combination of all health parameters; and 2. The application of an iterative optimal search for the reduce order tuner vector which is of appropriate dimension to enable Kalman filter estimation, while minimizing the sum of squared estimation errors in the parameters of interest.

Advantages of innovation: The advantage of the innovation is the significant reduction in estimation errors which it can provide relative to the conventional approach of selecting a subset of health parameters to serve as the reduced order tuning parameter vector. Furthermore, since this technique is only required to be performed during the system design process, it places no additional computation burden on the onboard Kalman filter implementation.

Test data and source of error: To date the methodology has been applied to parameter estimation in a generic NASA turbofan engine simulation. This simulation applies the methodologies commonly used throughout the aircraft engine industry for modeling gas turbine engine performance. Quantified estimation errors have been obtained using this NASA generic turbofan engine model as the "truth model." It is expected that there will be additional uncertainty if the technique were applied to an actual physical engine, instead of a model. However, the level of this uncertainty has not been quantified at this time.

Analysis of capabilities: The new methodology was evaluated using a linear engine model at a single operating point. Based upon this evaluation the new methodology was found to reduce parameter estimation errors by over 50% compared to the conventional approach for implementing the Kalman filter estimator.

Section IV — Potential Commercial Applications

Speculation regarding potential commercial application: The technique has been developed for aircraft engine onboard estimation applications, as this application typically presents an underdetermined estimation problem. As such, any aircraft engine manufacturer applying onboard model-based technology is a potential user of the technology. However, the technique is generic and could be applied by other industries using gas turbine engine technology.